ELECTRON OPTICAL SYSTEMS AND THEIR APPLICATIONS*

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PART I

ELECTRON OPTICS OF IMAGE FORMATION

The beginnings of electron optics can almost be said to pre-date the discovery of the electron itself. It was well known to the earliest investigators that an object in the path of a cathode-ray beam would cast a sharp shadow on a fluorescent screen which was bombarded by these rays. In this respect at least it was known that cathode rays resembled light rays.

It was not long after the discovery of the electron itself that such workers as Busch, Glaser, and later Knoll and Ruska, began the calculation of electron paths and thus laid the groundwork for the true science of electron optics. Since that time these trajectories have been studied in increasing detail as the importance of electron optics has become more and more widely recognized.

Of particular interest is the calculation of the paths through fields having radial symmetry. This type of field, either electrostatic or magnetic, can be shown to cause the electron paths to bend in a manner similar to the way in which light is bent when going through a lens. It is this possibility of replacing an electronic system by an analogous optical lens system that gives my subject its name, and this replacement by an optical analogue often (but not always) simplifies both qualitative and quantitative study of an electron " lens " system.

The behaviour of electrons passing through an aperture at potential V from a region of field strength ϵ_1 into a region of field strength ϵ_2 illustrates the similarity between electron rays and light rays. In this case the aperture will cause the electrons to converge just as would a spherical lens of focal length $f = 4V/(\epsilon_2 - \epsilon_1)$. Just as the glass lens will produce an image of a light source, so will the aperture be capable of producing an electron image. Furthermore, it has been shown that any cylindrical symmetrical configuration of an electrostatic field will produce either a positive or a negative lens action if the electron path is not too far from the axis of symmetry.

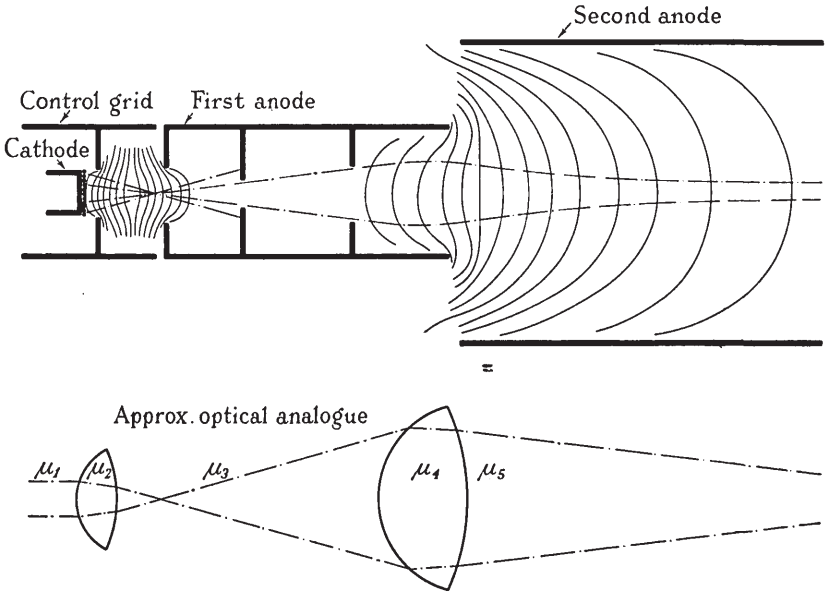

Fig. 1

$\mu_1 > \mu_2 > \mu_3 > \mu_4 > \mu_5$

It is not my purpose to present a theoretical study of the " optics " of electrons, as there are many excellent articles dealing with the subject, but rather to discuss certain practical details concerning the formation of electron images. Furthermore, I shall limit my discussion to the formation of images by means of electrostatic fields rather than systems involving magnetic lenses or combined magnetic and electrostatic lenses.

If electron optics had been of academic interest only, it would never have received the attention it has. Two of the most important practical applications, and the ones which have been most fully studied, are the electron gun and the electron microscope. The first is characterized by the requirement that a very small electron

* Reprinted from *Journal I.E.E.*, 1936, vol. 79, p. 1.

source is to be focused into a very small image or spot. In this case, both image and object are close to the axis of the lens, and factors such as curvature of the image field, distortion within the image, etc., are not of great importance. A typical example of an electron gun is shown in Fig. 1. This system consists of two lenses (shown in the optical analogue under the diagram of the gun) which produce on the screen an image, not of the cathode itself but of a point close to the cathode (known as the cross-over). This type of electron optics plays an important role in cathode-ray oscillographs in general and in cathode-ray television in particular. The latter application has already been described in the *Journal.** The final results of image reproduction depend almost entirely on the accuracy of electron-beam focusing at both the transmitting and receiving ends. An illustration of the progress in this field is shown in Fig. 2 (Plate 1, facing page 150), which is a photograph of a television image from a moving-picture film reproduced with 343 lines.

The second field of application, the electron microscope, is one in which electron optics is used to produce a very much enlarged image of a small object. Fig. 3

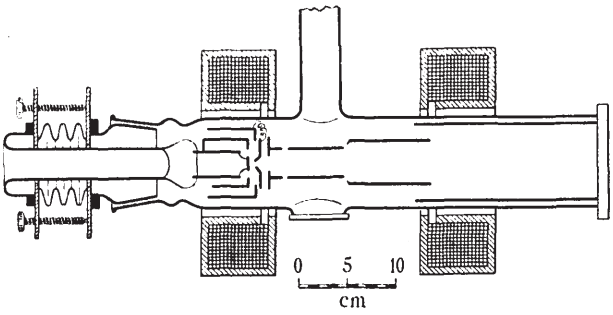

Fig. 3.—Typical electron microscope.

shows a typical electron microscope, illustrated in Brüche and Scherzer's excellent monograph on electron optics. There are a great many types of these microscopes, most of which make use of combined electrostatic and magnetic fields, but a discussion of them is beyond the scope of this lecture.

In the course of a study of electron optics carried out by the firm with which I am associated, there arose the problem of producing an electron image of an extended object; furthermore, it was necessary to do this solely by electrostatic means. The optical analogue of this system is the lens system of a copying camera. A satisfactory solution of this problem requires that (1) the image be free from distortion, (2) the circle of confusion be small, (3) the effective aperture of the lens large, and (4) the area of the object and image large. The magnification of this system should be close to unity, i.e. from 0·5 to 3.

As a basis for this system, let us consider the field between two coaxial cylinders of equal diameter. Fig. 4 illustrates diagrammatically this type of image tube. The cathode is a semi-transparent photoelectric surface, and the viewing screen is similar to those used in the cathode-ray oscillograph, formed by spreading a thin layer of special willemite on the glass end-plate of the tube. A potential is applied between the two cylinders, the cathode and adjoining cylinder being negative, while the screen and long cylinder are made positive. When a light image is projected on the photocathode, electrons are released in proportion to the intensity of the light falling on any given area. These electrons are focused by the electrostatic lens between the two cylinders into an inverted image on the fluorescent screen.

Since this system is to form the basis of the image tube, it is worth while to examine it in detail, from both a

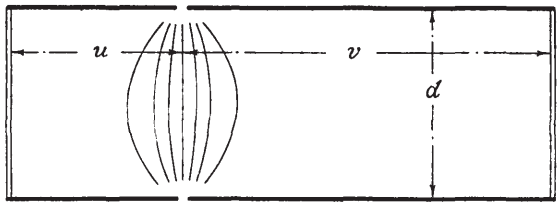

Fig. 4.—Lens system formed by coaxial cylinders.

theoretical and an experimental aspect. The potential distribution can be determined using the relations

$$\phi(z) = (\epsilon_2 - \epsilon_1)\frac{2}{\pi}\int_0^\infty \frac{\cos(2ku)\sin(2kz)dz}{kJ_0(jk)}$$

$$\phi''(z) = (\epsilon_2 - \epsilon_1)\frac{8}{\pi}\int_0^\infty \frac{k\cos(2ku)\sin(2kz)dz}{J_0(jk)}$$

$$\frac{d^2r}{dz^2} + \frac{\phi'}{2\phi}\frac{dr}{dz} + \frac{\phi''}{4\phi}r = 0$$

where z = distance along axis, u = distance between cathode and junction of two cylinders, and r = distance

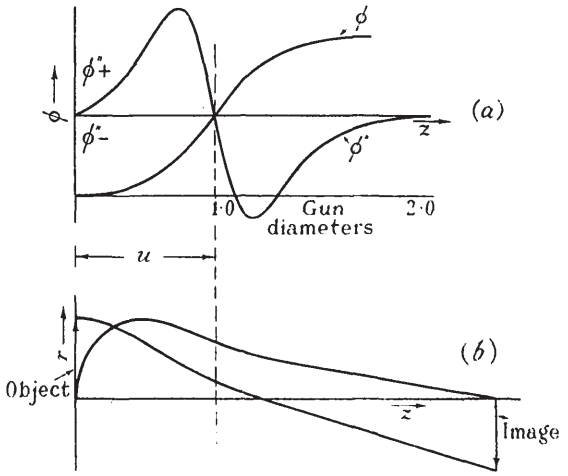

Fig. 5.—Electron paths.

measured at right angles to axis. A solution of the differential equation yields the axial potential distribution, which is shown in Fig. 5(*a*) together with the second derivative of the potential. From these the electron paths can be calculated by means of the well-known ray

* V. K. ZWORYKIN: "Television with Cathode-Ray Tubes," *Journal I.E.E.*, 1933, vol. 73, p. 437; and *Proceedings of the Wireless Section*, 1933, vol. 8, p. 219.

formula. Fig. 5(*b*) shows the path of an electron leaving the centre of the cathode at an angle to the axis, which gives us the image position; and also the path of an electron leaving the cathode with zero velocity from a point off the axis, giving us the magnification of the system.

The position of the image is determined by the distance u between the cathode and the junction of the two cylinders, which, for convenience, I shall call the " lens." Determinations of the lens-image distance v in terms of u have been made experimentally also, using a tube having a movable cathode and screen. Fig. 6 shows the results of both types of determinations, and also that over a wide range the magnification is quite accurately given by $v/(2u)$. It should be noted that the image position is independent of the difference of potential between the two cylinders.

The practical difficulty with this system lies in the fact that it is almost impossible to construct and mount the cylinders in such a way that the image will be perfectly in focus, and to construct the tube in such a manner that its mechanical dimensions can be changed after the tube has been exhausted and sealed is rather impracticable, though not impossible.

In order to focus the system electrically, it is necessary to change the curvature of the equipotential surfaces near the " lens " without so changing the field close to the cathode that the distortion of the image is increased. This could best be done by making the cathode-to-lens cylinder of resistive material, so that a potential gradient could be established along it. Experimentally, it is found that if the cathode cylinder is subdivided into four or more rings, each at a progressively higher potential, the distortion of the image is no greater than for the mechanically focused tube. The magnification of this type of tube is also given by $v/(2u)$.

These two types of tubes will give a fairly satisfactory image if the percentage of the cathode area used is small. The image suffers, however, from two defects: first, from pin-cushion distortion; and second, from the fact that a truly sharp focus can only be had at one value of the radius on the screen. Fig. 7 (Plate 1) is a photograph of the image obtained on the fluorescent screen when the entire cathode is illuminated with a rectangular grid. A study of the pattern shows that the image field is curved in such a way as to be convex from the lens side. Without changing the actual lens system, we have two means for correcting the above-mentioned distortion: first, by producing a radial gradient over the cathode; and second, by properly shaping the cathode surface.

The first method is not at present of much practical importance, but it is of interest theoretically. It can be applied by making the semi-transparent cathode film so that it is resistive, and then passing a current radially outward from the centre. The resistance of the film is not, however, uniform, but is lowest at the centre, increasing proportionally to the square of the radius towards the rim. By making the centre positive and correctly proportioning the resistance, both pin-cushion and de-focus effects can be corrected. Since electrical contact must be made to the centre of the film, however, it is impossible to avoid a blemish at the centre of the image.

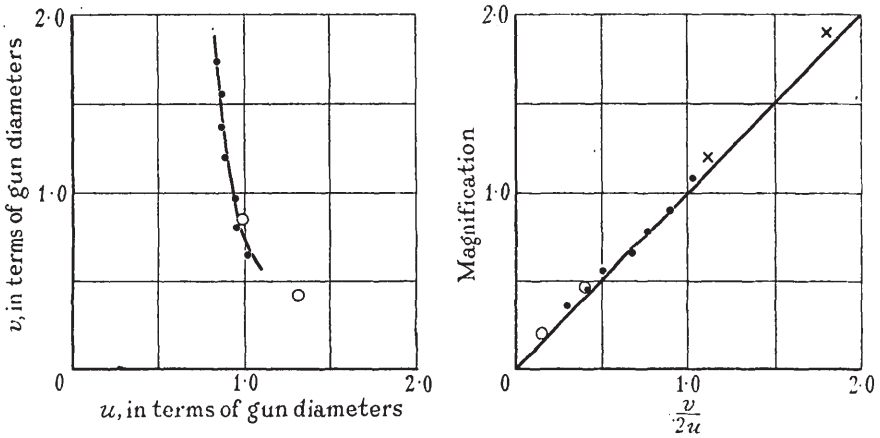

Fig. 6

● Fixed focus
× Variable focus } (experimental values).
○ Fixed focus (calculated values).

It is interesting to note that these cathodes can be made self-correcting for a given value of light by making the film of uniform high resistance. When this is done, the photoelectric current produces a gradient over the cathode just as did the radial current in the previous case. The disadvantage of this solution to the problem is that the correction is complete for one value of light only and, furthermore, the illumination over the optical image must be fairly uniform.

The second method, that of shaping the cathode, is much more practicable and can be made to yield an excellent image over the entire cathode area. In making this correction, the first thought might be that the cathode should be convex towards the lens in order to bring the centre of the object closer to the lens, thereby correcting both the pin-cushion distortion and curvature of the field. The primary cause of this distortion, however, is the change of the radii of curvature of the equipotential surfaces with distance away from the axis

near the plane cathode. Introducing a convex surface only accentuates this effect. If, however, the cathode surface is concave towards the lens, the shape of the equipotential surfaces may be so adjusted that a perfect image can be obtained. It is found experimentally that if the cathode is spherical and of radius equal to the lens distance u, very satisfactory results are obtained.

Fig. 8 shows diagrammatically the construction of an image tube with curved cathode and focusing rings. It should be mentioned here that it is unnecessary to bring out separate leads for each of the rings making up the focusing cylinders. Instead, the potential divider supplying the voltage to these rings can be mounted within the tube itself. A photograph of the same grid pattern as that used in Fig. 7 is shown in Fig. 9 (Plate 1). It will be seen that the image is uniformly sharp and that the pin-cushion distortion is negligible.

So far, I have spoken only of lens systems using no apertures. While the presence of apertures somewhat complicates our picture of the electrostatic field making up the electron lens, certain general features remain the

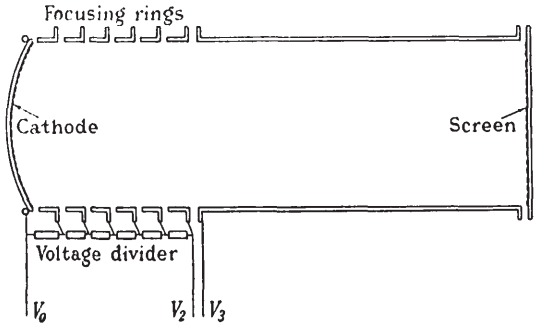

Fig. 8.—Image tube: fixed magnification

same. The field is cylindrically symmetrical as before, the lens system as a whole is positive and capable of producing a real image, and, finally, the same type of image distortion occurs as in the tubes described above—unless a corrected cathode is used.

Three arrangements of apertures applied to the type of tube just described are shown in Fig. 10. The first case is that of two symmetrical apertures. With this system the magnification will be found to be $v/(2u)$, as before, but the focal length for a given ratio V_1/V_2 is shorter. This means, in a practical case, that the voltage-difference between the anode cylinder and the final focusing ring can be made less, with a consequent simplification of the insulation problem and decrease in the danger of cold-cathode discharge.

Where the apertures are not symmetrical the magnification is no longer given by $v/(2u)$. If the aperture on the anode cylinder is smaller than the aperture on the final focusing ring, the magnification is greater than that given by the above relation, while if the anode aperture is the larger the magnification is less. The use of unsymmetrical apertures allows a wide variation in magnification in tubes which otherwise have identical construction.

The final case to be considered is that shown in Fig. 11. This type of lens system has an aperture placed midway between the anode cylinder and the final focusing ring whose potential V_3 can be varied. It should be noted that when the aperture potential V_3 equals the anode voltage, the conditions are similar to those of the case just described where the aperture on the anode cylinder is smaller than that on the focusing ring, and the magnification will be greater than $v/(2u)$. Likewise, when V_3 is made equal to the ring potential, the magnification is

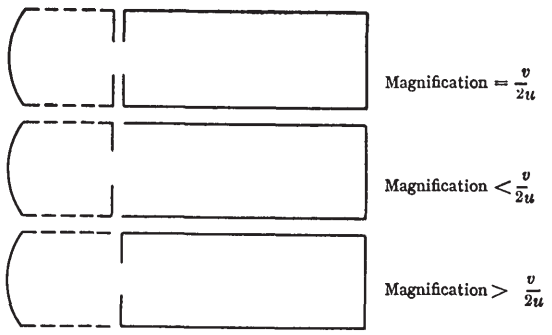

Fig. 10.—Arrangement of apertures in image tube.

a minimum. For intermediate values of V_3 the magnification lies in between these extremes.

The pin-cushion distortion is a maximum when V_3 is equal to ring potential or less, but decreases rapidly to a constant value as V_3 is increased. Over nearly the entire range of magnification, a curved cathode will correct this distortion fairly satisfactorily. With this arrangement it is possible to construct a tube which gives a very satisfactory image and whose magnification can be controlled electrically.

An interesting use to which this type of tube may be put is exemplified in the electron telescope. A large-aperture lens is mounted so as to form an image of the scene towards which the telescope is pointed, on an infra-red sensitive cathode of an image tube. The electron picture falling on the fluorescent screen renders visible

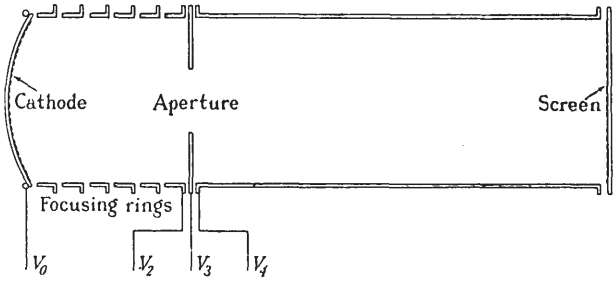

Fig. 11.—Image tube: variable magnification.

the infra-red image. Such a device can be used to test haze and smoke penetration by infra-red rays, for signalling, etc.

Another use is in connection with infra-red microscopy. Fig. 12 (Plate 1) shows an image tube and microscope arranged for infra-red work. The visible image on the fluorescent screen of a micro-specimen is shown in Fig. 13 (Plate 2). Black gum was used in this case as the packing material.

The next two pictures (Figs. 14 and 15, Plate 2) were made by photographing the fluorescent screen while an

infra-red picture was projected on the cathode. They illustrate fairly well the resolution and fidelity of the image obtainable. Fig. 16 (Plate 2) is a photograph of the electron telescope, and Fig. 17 (Plate 2) a photograph of an image tube with 9-in. screen.

PART II

SECONDARY-EMISSION MULTIPLIERS AND ELECTRON OPTICS

Leaving, now, electron optics as applied to image formation, I propose to discuss another field in which its application is extremely important. This is the field of secondary-emission multipliers. In this section, emphasis will be placed on the general design and operation of these multipliers rather than on electron optics; but the important role that this science plays will be very apparent.

It has been known for many years that when certain surfaces are bombarded with cathode rays they emit electrons. This effect, known as secondary emission, has, from an early date, been extensively studied by a large number of workers such as Lenard, Hull, and Von Bayer. The study of this phenomenon revealed that the number of electrons emitted is proportional to the bombarding current, the factor of proportionality ranging from a mere fraction to 10 times as many secondary as primary electrons. The value of this ratio depends upon the surface used and on the velocity of the bombarding electrons.

Although these facts have been known for a long time, the effect had not until recently found any useful application, except in the case of the dynatron invented by Dr. Hull. In fact, secondary emission had chiefly been looked upon as a serious obstacle in the design of thermionic vacuum tubes, and much research had been carried on with a view to suppressing and reducing it. During the past 15 years it became recognized that secondary emission could be used as a means of amplifying a small initial electron current, and a number of workers began investigating in this field. Patents for methods of applying this idea were filed as early as 1919 by Slepian,* and later by such workers as Jarvis and Blair,† Iams and Salzberg,‡ Farnsworth, and others.

The general method involved is to allow the initial electron stream to impinge upon a target which has been sensitized for secondary emission. The secondary electrons from this target are directed on to a second target, producing still further electrons, the multiplication being repeated as many times as is desired. Reference to Fig. 18 will make this process clear. In this figure, electrodes A, B, C, etc., represent a number of plane targets having a high secondary-emission ratio. These electrodes are connected to successively higher positive potentials. The stream of electrons to be multiplied is directed against A. This target gives rise to secondary electrons which go to target B, in turn giving rise to secondary electrons which are directed against C. After this process has been repeated a sufficient number of times to give the desired overall multiplication, the electrons from the final target are collected on collector O. If s be the number of secondary electrons per primary for each stage and n the total number of stages, then the initial current I_0 will be multiplied up to an output current $I_0 s^n$. Clearly, the overall gain will be s^n times. It will be seen that the overall gain becomes very large indeed as the number of stages is increased.

A second class of multipliers has been described by P. T. Farnsworth* in which the electrons are made to go back and forth between a single pair of targets, getting their energy from a high-frequency electric field. Of these two classes of multipliers, only the static type using successive targets, wherein the number of impacts can be rigorously controlled and the stability is consequently very great, will be discussed in this paper.

The problem of making a multiplier to give high gain is not, however, so simple as it might seem at first sight. A simplified multiplier constructed in accordance with the diagram (Fig. 18) would be almost completely inoperative, for the reason that practically all the electrons leaving any target would not go to the following one, but would merely go down the length of the tube and be collected at the final collector with almost no multiplication.

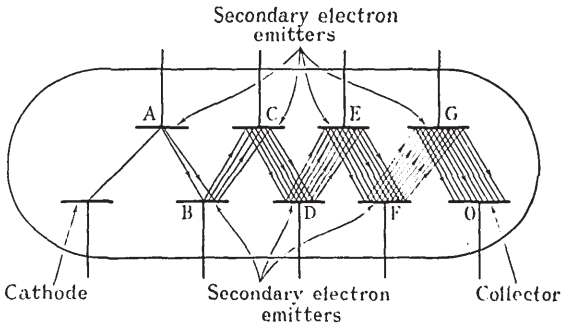

Fig. 18.—Simplified secondary-emission multiplier.

In order to construct a successful multiplier, not only must the target have a high secondary-emission ratio, but also means must be provided to focus the electrons on to each target, and to draw away secondary electrons from one target preparatory to focusing them on to the next succeeding target.

Before taking up the methods of electron focusing employed in specific multipliers, I shall discuss certain general aspects of fixed-field multipliers.

(1) General Considerations

(a) Secondary Emission.

Since the successful operation of these multipliers depends upon a high secondary emission from the targets, it is of prime importance to discover the most suitable surfaces to use. In our search for good emitters, very little aid can be obtained from the theoretical physicist. The most complete treatment of the theoretical aspect of secondary emission in the light of quantum mechanics was published by H. Fröhlich† in 1932.

In this discussion he calculates the probability of the transfer of energy between an incoming primary electron and a conduction electron moving in the periodic potential field of the metal, where the exchange is such

* Patent No. 1450265, 3rd April, 1923 (1919).
† Patent No. 1903569, 11th April, 1933 (1926).
‡ *Proceedings of the Institute of Radio Engineers*, 1935, vol. 23, p. 55.

* "Television by Electron Image Scanning," *Journal of the Franklin Institute*, 1934, vol. 218, p. 411.
† *Annalen der Physik*, 1932, vol. 13, p. 229.

as to give the conduction electron sufficient momentum to escape from the metal. On this basis, he concludes that metals with a crystal structure having a large lattice spacing and with a low work function should be the best secondary emitters. This treatment, however, applies only to simple metal surfaces.

Experimentally, it has been found that the emission ratio from simple metal surfaces is invariably below that obtained from composite surfaces, just as with photo-

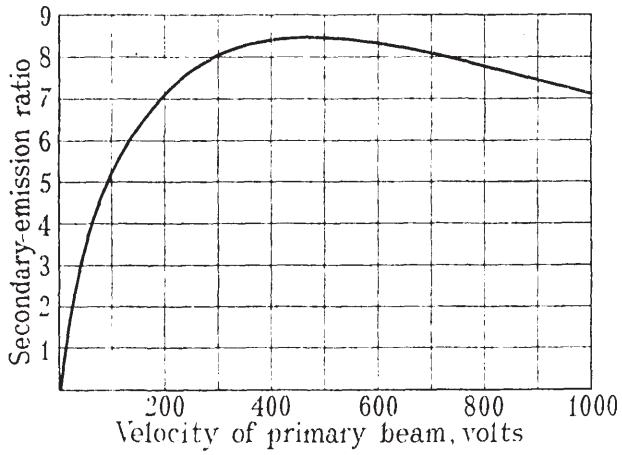

Fig. 19.—Ratio of secondary-emission current to primary current for Cs-CsO-Ag surface.

electric emission. Since the theoretical knowledge of secondary emission does not extend to these composite surfaces, it is necessary to go ahead on a more or less empirical basis, keeping in mind that, other things being equal, a surface of low work function is the most likely to be a good emitter. A large number of low work-function surfaces were therefore studied having as a base metal Ag, Be, Ta, Ni, Al, Zr, Ca, W, etc., and Na, K, Rb, and Cs as a surface layer. Of these, the most satisfactory to date have been oxidized Ag, Be, or Zr, with a surface layer of caesium. These surfaces have a maximum ratio of from 8 to 10, occurring at a bombarding velocity of from 400 to 600 volts.

A curve showing the secondary-emission ratio of a Cs-CsO-Ag surface for various bombarding voltages is given in Fig. 19. This is typical of the surfaces frequently used in the multipliers to be described later. The method of preparation of this surface is very similar

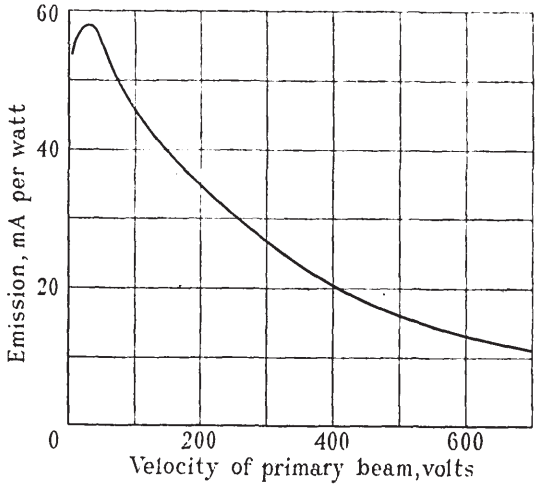

Fig. 20.—Curve of current per watt for secondary emission of Cs-CsO-Ag.

to that used in the preparation of the photoelectric cathode for a high-vacuum caesium photocell.

(b) Multiplier Efficiency.

There are two ways of considering the efficiency of a multiplier. The first is to measure the efficiency of secondary emission as a source of electrons, in terms of amperes per watt supplied; while the second considers gain obtainable for a given overall voltage as a function of the number of stages and the voltage per stage. The

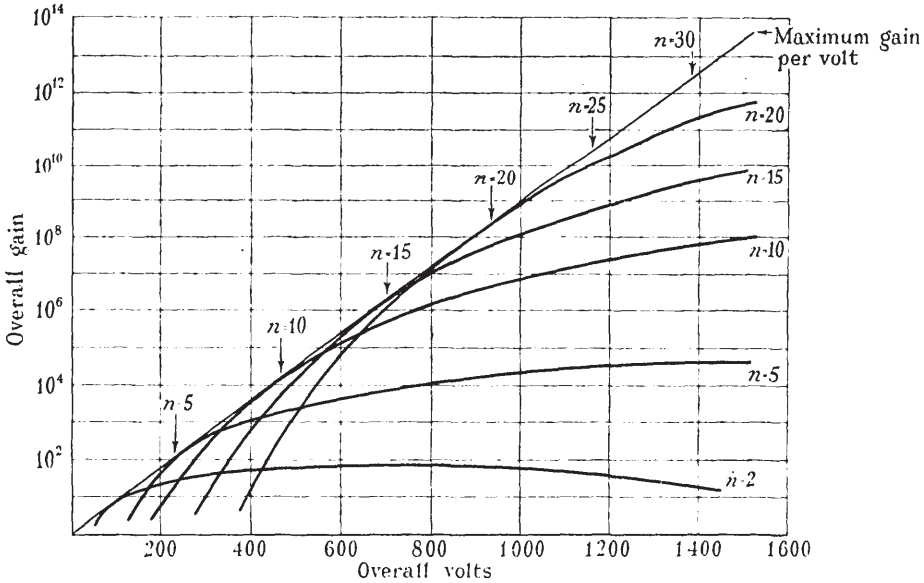

Fig. 21.—Gain obtainable with secondary-emission multiplier.

second of these two considerations is more important from a practical standpoint, but both are worthy of some discussion.

From Fig. 19 the curve of the emission plotted against bombarding voltage, as shown in Fig. 20, can readily be calculated. This curve shows that the maximum emission, which occurs at about 30 volts, is 60 mA per watt (a gain of 0·06 per volt), dropping to 45 mA per watt at 100 volts, and 17 mA per watt at 500 volts. For comparison, it may be mentioned that a good thoriated-tungsten thermonic cathode will deliver 50 to 75 mA per watt, while an oxide-coated cathode may give as much as 100 mA per watt. Thus, while secondary emission is not the most efficient way of obtaining an electron current, it compares rather favourably with other methods.

The question of maximum overall gain will be made clearer by reference to Fig. 21. This family of curves shows the gain that can be obtained from multipliers with various numbers of stages, plotted against voltage. These curves show that the most efficient multiplier is one operated with 40–50 volts per stage. Run in this way, such a multiplier gives very high gains. For example, a 10-stage multiplier at 500 volts will have a gain of 30 000, while a 15-stage multiplier at 800 volts will multiply the initial current 10 million times. It should be noted that the curves in Fig. 21, and the overall voltages given, do not include the voltage between the collector and the last target, as this will depend upon the use to which the tube is to be applied.

(c) Noise in Multiplier Output.

Turning now to the question of noise, which is the limiting factor in the amplification of these multipliers, we have to consider chiefly the statistical fluctuation of the useful electron current through the tube. From theoretical considerations verified by experiments, it can be stated that the signal/noise ratio obtainable from multipliers is practically that determined by the shot effect in the original photo-electric current.*

There are two other factors which limit the sensitivity of these multipliers; they are (i) thermionic emission from the secondary emission targets, and (ii) noise due to the positive-ion emission. These two factors, while troublesome, can be overcome if proper precautions are taken. Therefore, it may be said that the shot noise of electron emission sets the fundamental limit to the sensitivity of the secondary-emission multiplier. For low light intensities the gain in signal/noise ratio is from 60 to 200 times when compared with an ordinary amplifier under usual operating conditions.

* A. W. Hull and N. H. Williams: *Physical Review*, 1925, vol. 25, p. 147; F. M. Penning and A. A. Kruithof: *Physica*, 1935, vol. 2, p. 793; L. J. Rayner: *Physics*, 1935, vol. 6.

(d) Frequency Response.

The frequency response of the secondary-emission multiplier is flat over a very wide range of frequencies. Between the upper limit and a direct-current signal, the frequency response is essentially uniform.

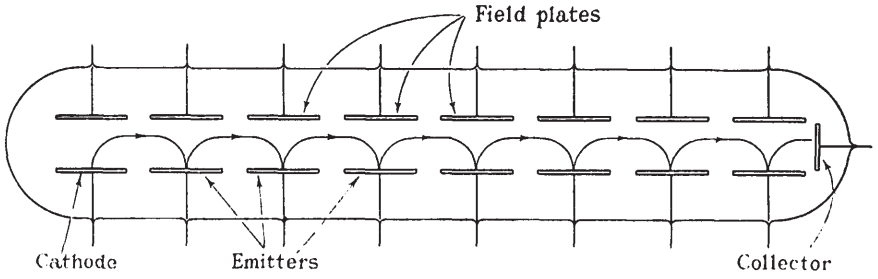

Fig. 22.—Magnetic secondary-emission multiplier.

(2) Magnetic Secondary-Emission Multiplier

(a) Theory of Operation.

We shall now consider an electron multiplier with crossed magnetic and electrostatic fields, designed to separate and focus the secondary electrons from one target to the next. This configuration of fields and electrodes was first suggested by Slepian in 1919, for use as a high-current cathode.

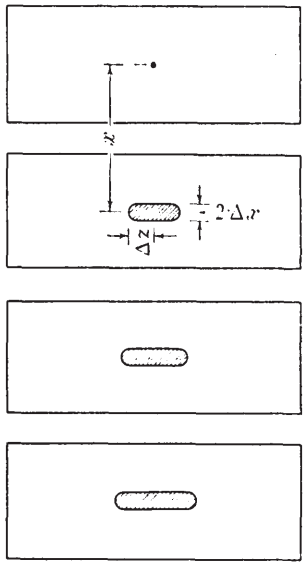

Fig. 23

The general arrangement of a multiplier based on this principle is shown in Fig. 22. It consists of two rows of electrodes, the bottom row being secondary emitters, while the upper row serves solely to maintain a transverse electrostatic field between the two sets of elements.

Each target in the bottom row is made positive with respect to the preceding one so that it will produce secondary electrons when struck by electrons originating from the latter. A magnetic field is established in the tube at right angles to its axis and to the field between the two rows of plates. Electrons leaving any of the lower plates are bent by the combined fields in such a way that they strike the next target, giving rise to secondary electrons, which are in turn deflected on to another target, and so on, through the tube.

Under the influence of these two fields, electrons are separated from the primary and are focused on succeeding targets. This focusing can be compared with that of a cylindrical optical system, in that the focusing can be almost perfect in one direction but very ineffective in the opposite direction. This means that electrons leaving from a point on the cathode are spread into an elliptical spot on the first target. This spot, in turn, is spread into a larger ellipse on the second target, the size of the spot increasing as the electrons progress down the tube. This effect is illustrated schematically in Fig. 23.

Eventually, the spot becomes so large that some of the electrons miss the target entirely, and there is a dropping-off of the efficiency of the subsequent stages. The transverse spreading is such that there would be a serious loss after a comparatively few stages unless special precautions were taken to prevent this type of defocusing.

(b) Design and Construction of Magnetic Multiplier.

A schematic diagram of the actual application of the principles described above to a multiplier photocell, is shown in Fig. 24. Photo-electrons are focused upon a target 1a. Secondary electrons from this electrode will be focused on target 2a, giving rise to further electrons, and so on, for as many stages as is desired.

The plates are mounted in the tube in such a way that the upper and lower plates are as close together as is possible in order to make the potential gradient large and thus increase the current that can be drawn away from a target before space-charge limitations occur. This minimum spacing is half the distance between centres of successive targets. With this construction it is found that the current which can be drawn from the tube is limited only by the power that can be dissipated from the final stages in overcoming the heat generated due to electron impacts.

In order to limit the sideway spreading, the electrodes are mounted on vertical strips of mica. Charges which accumulate on these vertical walls so alter the field as to introduce an additional lens action which limits sideway spreading. With this arrangement the limit to the number of stages which may be used is set by the axial defocusing, but this defocusing is so small as to permit the use of a great many stages. The upper limit to the number of stages has not been determined experimentally, although multipliers employing as many as 12 stages without a decrease in gain per stage have been constructed.

When multipliers are operated at high gains into high-impedance loads, some difficulties are encountered due to oscillation. This can be eliminated by surrounding the collector electrode with a shield grid, as shown in Fig. 24. The grid serves as an electrostatic shield and prevents

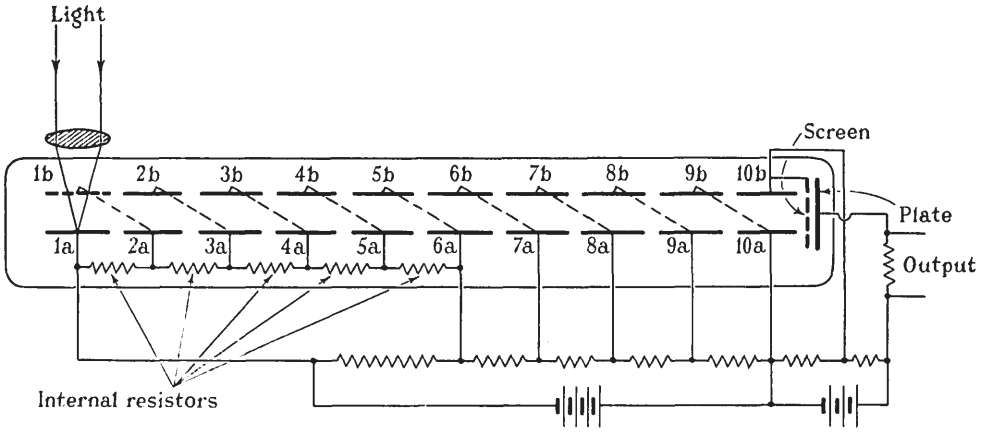

Fig. 24

changes of collector potential from reacting back upon earlier stages. It also results in the output characteristic being altered from that of a triode to that of a conventional screen-grid tetrode.

For operation of the device, it is necessary that the upper electrodes be at a fixed positive potential with respect to the corresponding lower electrode, and that the voltage-steps between adjacent electrodes be equal. In order to decrease the number of leads required, it has been found advantageous to connect upper electrodes to lower targets farther down the tube. Satisfactory results have been attained with each upper electrode connected to the next succeeding lower target.

Since the first few targets draw almost no current, their potential can be very satisfactorily supplied from a voltage-divider or bleeder. In order to decrease further the number of leads in a multiplier employing many stages, it has been found practicable to incorporate the bleeder for the initial stages inside the tube.

It has also been found possible to operate the device with alternating voltages on the electrodes. The operation will, of course, occur over only a portion of each cycle. The frequency of the applied alternating current must exceed the highest frequency which the multiplier is to transmit.

Fig. 2

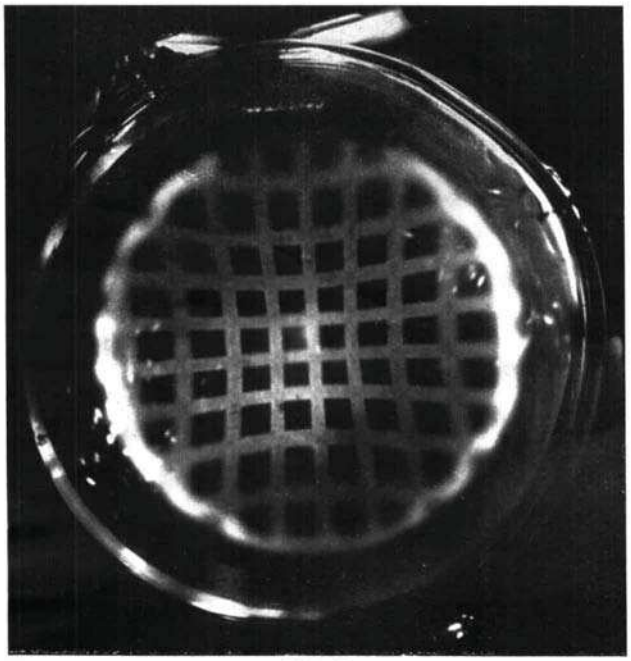

Fig. 7

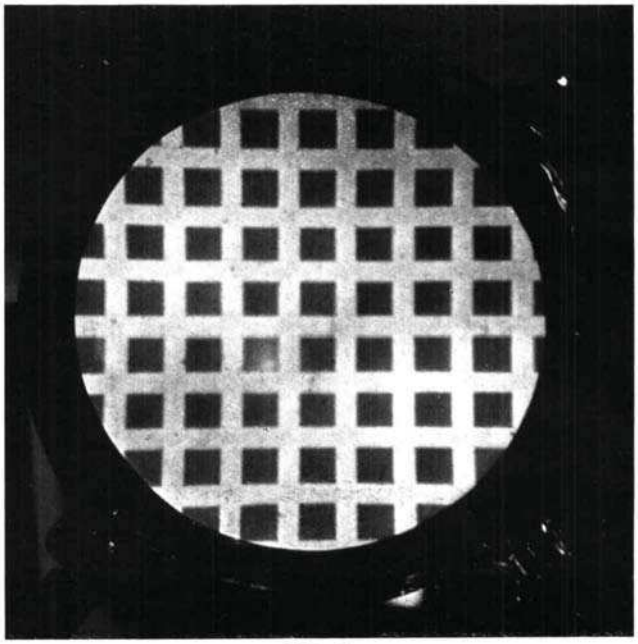

Fig. 9

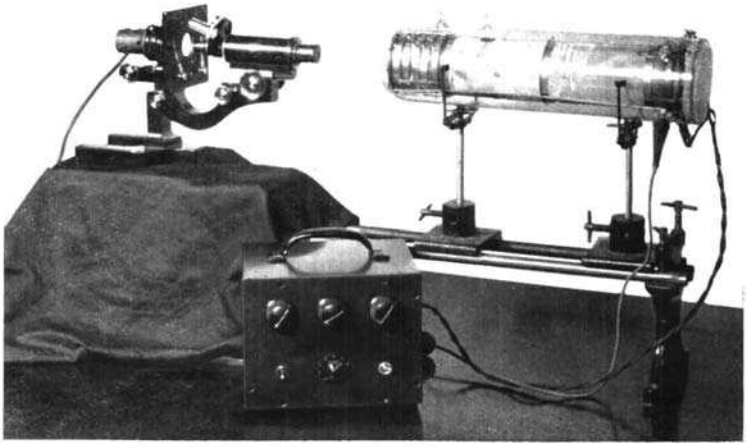

Fig. 12

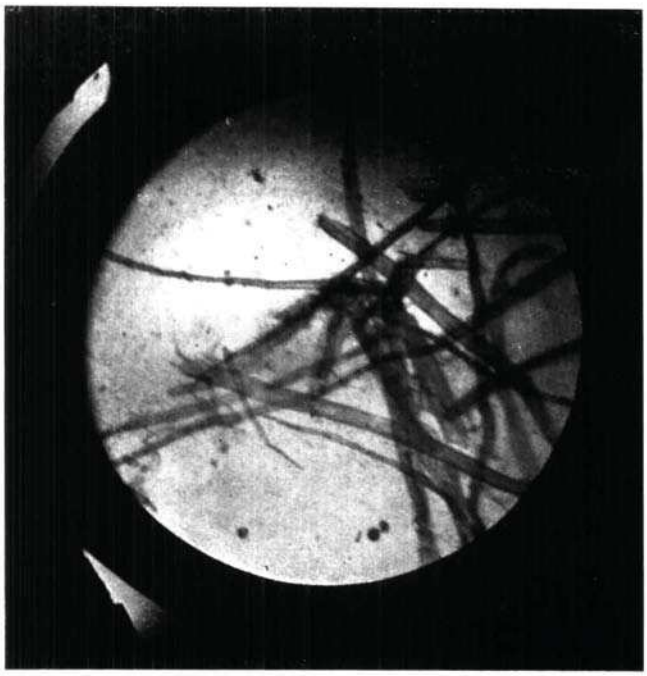

Fig. 13

Fig. 14

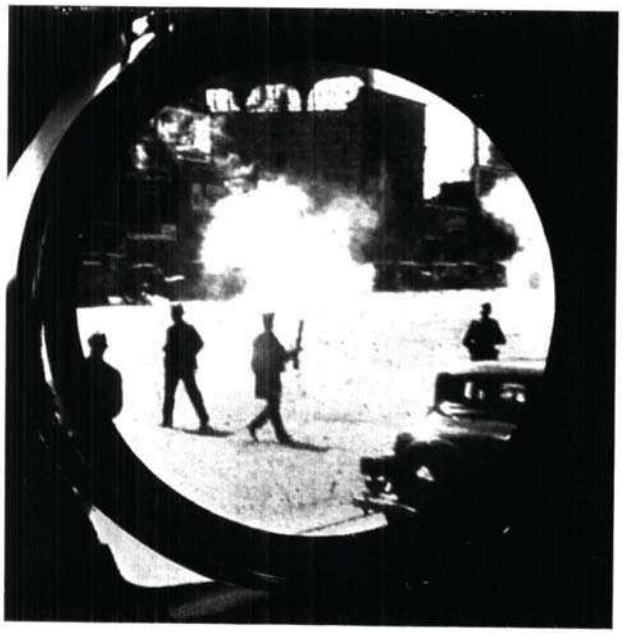

Fig. 15

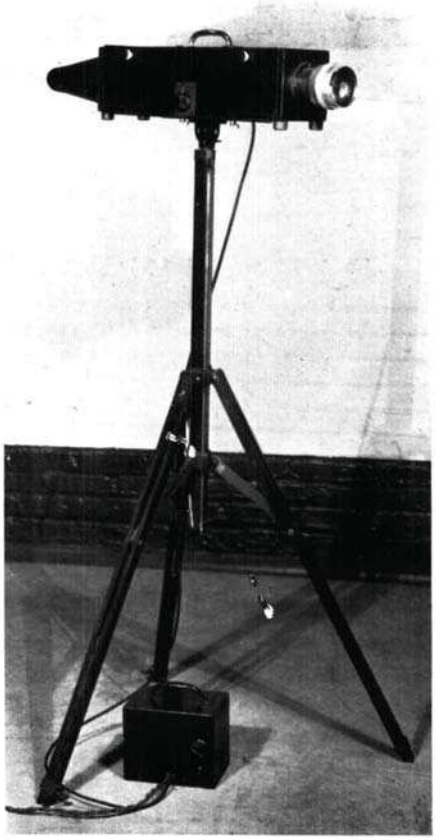

Fig. 16

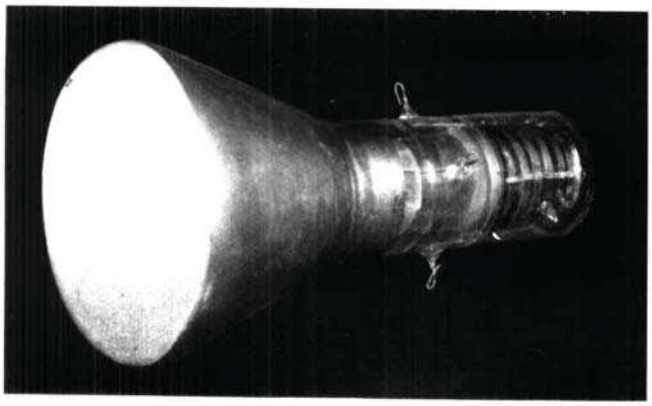

Fig. 17

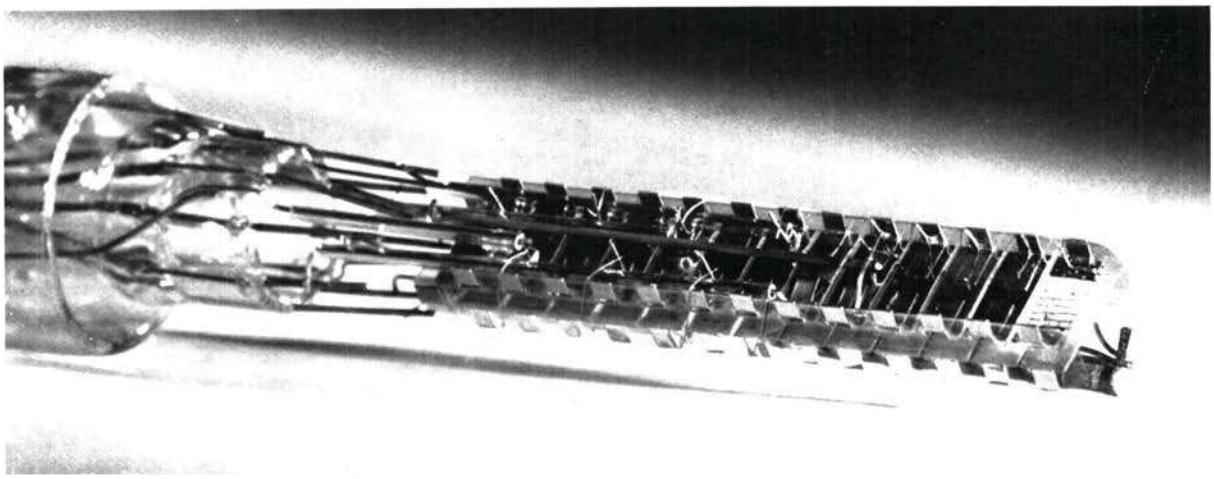

Fig. 25

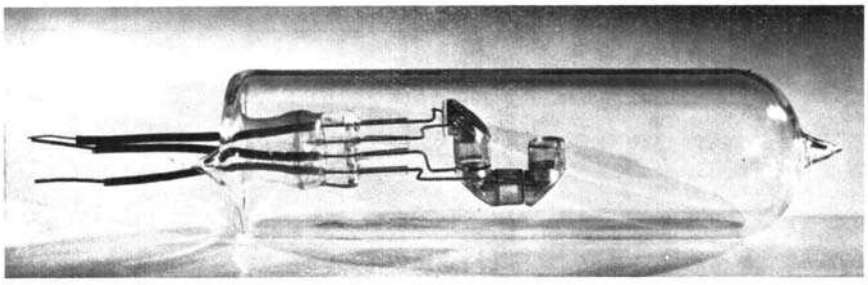

Fig. 29

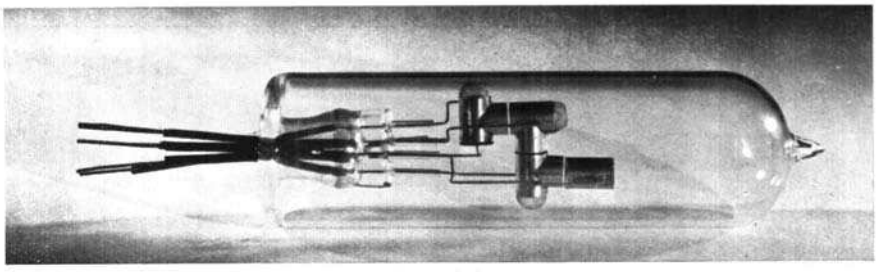

Fig. 30

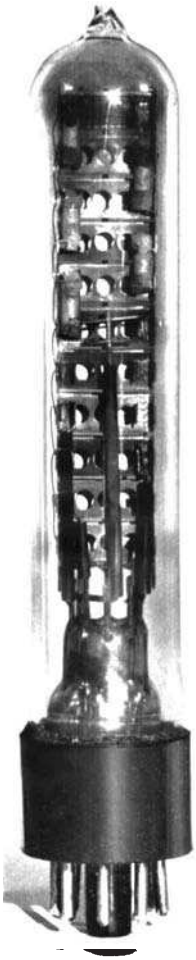

Fig. 31

Fig. 32

As a means of supplying the requisite magnetic field, permanent magnets have been found to be very satisfactory. These are superior to electromagnets from the standpoint of size and also in view of the fact that no external power is required.

An enlarged photograph of the internal structure of a 12-stage multiplier in which the voltage divider for the first five stages is incorporated in the tube, is shown in Fig. 25 (Plate 3).

(3) Electrostatic Multiplier

Where the application of a secondary-emission multiplier does not permit the use of a magnetic field, it is necessary to use a multiplier in which the electrons are focused by electrostatic fields alone.

The problems involved in designing the focusing system for such a multiplier are similar to many of those met with in an electron microscope. It can be shown that in general a radially symmetrical electrostatic field will have the properties of a lens over portions of the field near the axis of symmetry. The radial distance from the axis over which this condition applies will depend upon the field configuration. The focusing system of the electrostatic multiplier is based on the field between two coaxial cylinders. Since it is desirable to have a minimum of separate voltages to operate the tube,

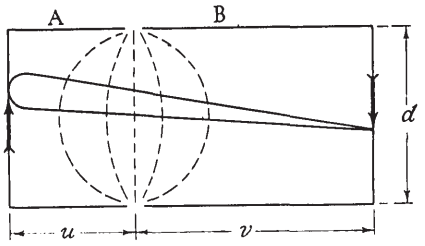

Fig. 26

$u \simeq \frac{1}{2}d$
$v \simeq \frac{1}{2}d$
Magnification = 1

one cylinder is made part of one target while the other is connected to the next succeeding emitter. The configuration is made such that electrons from an area in the centre of the first target will come to a focus at the centre of the next, and that the magnification of the electron image formed will be unity.

This electron " optical " system is similar to those described earlier in this paper and will be made clear by reference to Fig. 26. In this diagram the lens is formed between the cylinders A and B, A being at earth potential, while B is at the potential V. The electrons are emitted from the cathode in A with a very low velocity, are deflected by the " lens " formed between the two cylinders, and are focused on to the screen or electrode in B, striking it with a velocity of V electron volts.

The application of this optical system leads to the so-called " L " type multiplier whose construction is shown in Fig. 27. This multiplier is quite satisfactory from the standpoint of focus, but the field at each target drawing away the secondary electrons is rather weak and the multiplier becomes space-charge-limited at rather small current values. Further, the emitting spot on the initial cathode must be small if accurate focus is to be maintained.

A second type of multiplier has been designed which does not depend upon so sharp a focus and which has a

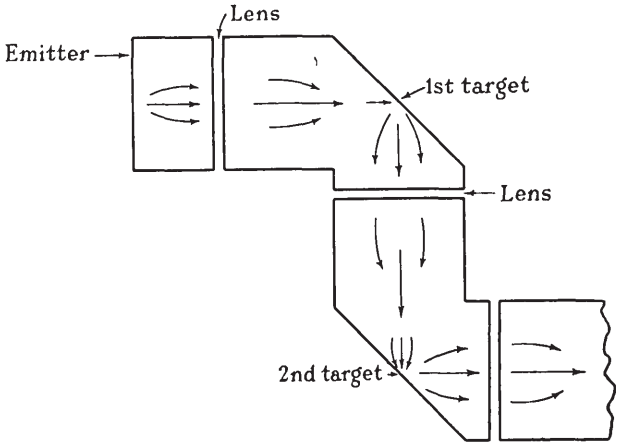

Fig. 27.—" L " type multiplier.

higher collecting field at the targets. This is the " T " type multiplier which is shown in Fig. 28. This multiplier is built so that the cylindrical exits from the targets are as short as possible and yet long enough to ensure that electrons entering through the stem of the " T " will not be deflected sufficiently by the field from the succeeding electrode to miss the target. The targets are formed by sensitizing the whole inside of the cylindrical cross-arm of the " T." Even with this arrangement, where currents of the order of 1 milliampere are to be used it is necessary to operate the multiplier at a fairly high voltage per stage, i.e. 200–400 volts, if space-charge

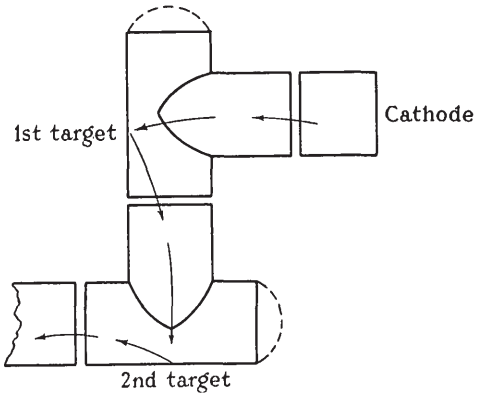

Fig. 28.—" T " type multiplier.

effects are to be avoided. Figs. 29 and 30 (Plate 3) show multiplier photocells of the " L " and " T " types.

(4) Applications

The most obvious application of these multipliers is as photo-electric amplifiers. This use is very much simplified in view of the similarity between the photoelectric and secondary emissive surfaces. The most convenient type of multiplier to use for this purpose is the type com-

bining electrostatic and magnetic fields, because of the excellent focusing characteristics and the high current output obtainable. A tube of this type having a gain of several millions or an output of 10 or more amperes per lumen is but little larger than an ordinary receiving tube. A voltage of about 1 500 volts is required to operate such a tube, and since the current consumed is small it may be supplied from a small socket power unit.

Since it serves to replace not only a photocell but also its accompanying amplifier, there is obviously a great gain in simplicity and a saving in bulk. In addition, these multipliers are very stable, insensitive to external interference, and have an excellent frequency characteristic. An even more important factor is that the noise output is determined by the shot noise of the photoelectric effect, and therefore allows an increase of 60 to 100 times in signal/noise ratio under ordinary operating conditions for extremely low values of light. These facts combine to make this type of multiplier a very excellent means of converting a light signal into an electrical signal. The size of this tube may be compared with that of a conventional receiving tube by referring to Figs. 31 and 32 (Plate 3), which show to the same scale a 10-stage multiplier and an R.C.A. Type 59 tube respectively.

The applications of multiplier photocells are extensive, including in particular those of pick-up from sound film, facsimile, automatic door control, alarm systems, automatic sorting machines, etc.

Although at present the most important application of the secondary-emission multiplier is as a photocell, it has a number of other applications which may become increasingly important. In general, these multipliers can be used in connection with any device where the signal to be amplified is generated in the form of an electron current. This use includes types of electron commutator tubes such as are used for high-speed switching, secret sound systems, and frequency multipliers.

As a voltage-controlled amplifier, the device does not lend itself so readily. This is because, in general, to couple the input of a voltage-controlled amplifier to its external circuit it is necessary to use some form of coupling impedance, and this, as in the case of a conventional thermionic amplifier, will limit the signal/noise ratio obtainable. If the conventional type of thermionic cathode and control grid is used in connection with a multiplier, the problem of securing results superior to those obtainable with an ordinary vacuum tube presents considerable difficulties. There is the possibility of obtaining a higher percentage control per volt applied to the grid by deliberately throwing away a large fraction of the cathode current to gain this control, and then using a multiplier to bring the average current back to a higher level. This idea is still in its initial experimental stages, and it is too early yet to say what the outcome will be.

The secondary-emission multiplier is too new an instrument for it to be possible to foretell the full extent of its application; but even now it seems evident that it may become a serious rival to the thermionic amplifier in many of the fields which this has occupied alone for so long, and it may also open up new fields in the realm of the electronics of small currents.

In conclusion, I wish to express my thanks to Dr. G. A. Morton and Mr. L. Malter, who were associated with me in the work described in this lecture, and to acknowledge the valuable assistance rendered by the other members of the Electronic Research Laboratory of the R.C.A. Manufacturing Co., Inc., Camden, New Jersey.